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FAULTS ON THE GULF COASTAL PLAIN

February 27, 2012

AVILES ENGINEERING CORPORATION
5790 Windfern
Houston, Texas 77041

Attention: Wilber L. Wang, P.E.

SUBJECT: PHASE I GEOLOGIC FAULT INVESTIGATION FOR A WATERLINE THAT WILL PASS ALONG MONROE ROAD BETWEEN AIRPORT BOULEVARD AND ALMEDA GENOA ROAD, SOUTHEAST HOUSTON, TEXAS.

Transmitted herewith is my report on a Phase I geologic fault investigation for a waterline route to be constructed along Monroe Road between Airport Boulevard and Almeda Genoa Road at Moers Street in southeastern Houston. Included are illustrations that mark the location of 7 active faults that the line will cross.

I appreciate the opportunity to conduct this investigation. Please let me know if I can provide you with additional information or assistance.

Sincerely yours,

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PHASE I GEOLOGICAL FAULT INVESTIGATION OF MONROE ROAD BETWEEN AIRPORT BOULEVARD AND ALMEDA GENOA ROAD SOUTHEAST HOUSTON, TEXAS

For

THE CITY OF HOUSTON, TEXAS

Through

AVILES ENGINEERING CORPORATION
5790 WINDFERN
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By

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ILLUSTRATIONS

PHASE I GEOLOGICAL FAULT INVESTIGATION OF MONROE ROAD BETWEEN AIRPORT BOULEVARD AND ALMEDA GENOA ROAD SOUTHEAST HOUSTON, TEXAS

I. INTRODUCTION

The City of Houston plans to construct a 2-mile long waterline near the east side of Hobby Airport in southeast Houston. The line will pass primarily within the northbound lanes of Monroe Road between Airport Boulevard and Almeda Genoa Road at Moers Street (Plate I). This area lies between two large salt domes; the South Houston Dome centered about 2.3 miles to the northeast and the Mykawa Dome 3.0 miles to the southwest. The domes are somewhat cylindrical columns of salt that have risen upward from a salt layer approximately 40,000 feet below ground level. The salt rose slowly over tens of millions years, producing numerous geologic faults over the tops of the domes and radially outward from their flanks. Because the two domes are so closely spaced, their flanks nearly touching at a depth of about 6000 feet, an unusually large number of faults extend between them. No other place in Harris County has such a dense concentration of faults. Of great significance to the present study is that the interdomal area is currently undergoing regional extensional strain in an east-southeasterly direction, and current strain rates are high enough to produce active faults. All the faults are "normal faults" which dip (slope downward) steeply toward the downward moving fault block. Only extensional strain can produce such faults. A later section of this report will address the question of how the design life of a pipeline might be increased in an area of ongoing extensional strain.

Each of the 7 faults to be crossed by the pipeline trend 30 to 35 degrees east of true north, while Monroe Road trends due north (Plate I). At ground level, all 7 faults disturb near-surface soils in deformation zones a few tens of feet wide, measured perpendicular to their trends. However, the "apparent width" of the deformation zones along Monroe Road will be approximately 85% greater than their true width, due to the crossing angle. A single exception is Fault No. 10, which crosses Monroe Road at a small angle a few hundred feet south of Airport Boulevard. Here the roadway remains in the fault zone for a distance of at least 200 feet. No fault crosses the small east-west section of the route between the Monroe-Almeda Genoa intersection and Moers Street.

The present study provides the location and orientation of each fault, an estimated width of the zone of disturbed ground along the fault, and the geometric pattern of relative motion of the fault blocks. The <u>fault zone</u> is defined as the band of disturbed ground along the fault in which 90 percent or more of differential movement of ground between the upthrown and downthrown fault blocks takes place. The fault trace is a line connecting points along the edge of the upthrown fault block. It marks the part of the fault zone where relative motion between the fault blocks proceeds at the highest rate. As used here, the term "fault movement" refers to differential movement of ground across the fault zone. The fault zone itself does not change its geographic location with time.

The objectives of the present study are to:

1) Establish the location of 7 fault traces that cross Monroe Road between Airport Boulevard and Almeda Genoa Road.
2) Establish the 2-dimensional orientation of each fault where it crosses Monroe Road.
3) Estimate the true width of the fault zones, measured in a direction perpendicular to their trends.
4) Establish the 3-dimensional pattern of differential ground movement within the zone so that structures can be designed to accommodate it.
5) Estimate of the rate of differential ground movement across the fault zones.

The objectives are achieved by using data reported in previous studies of Hobby Airport area faults, and by obtaining new measurements at ground level. No subsurface data were obtained in the course of the present study. Nineteen proprietary studies, dating back to 1980, provided data on the precise locations of points on some faults. A few studies reported estimated widths of fault-disturbed zones, and fewer yet reported former rates of differential ground movement across the zones. Fault zone widths can be determined by measuring elevation profiles across fault-disturbed, man-made structures. Rates of fault movement have been obtained from recording the amount of deformation undergone by man-made structures of known age. A better method is to record progressive changes in elevation of benchmarks placed across a fault zone, but to the best of my knowledge, no such data are available for any fault in the Hobby Airport area.

II. GENERAL CHARACTERISTICS OF THE FAULTS

All 7 faults trend N 30-35 E, but locally the trends may vary several degrees outside that range. Fault lengths range from 0.13 to 2.48 miles. In some cases Monroe Road crosses near the center of a fault where its long-term movement rate is greatest. In other cases the road crosses near the end of a fault where movement rates die to zero. Here it is not possible to determine the fault's location precisely in the field or on aerial images of the ground surface.

All of the faults dip (slope downward) in a direction perpendicular to the trend of the fault. Four faults dip to the northwest, three to the southeast. Plates I and II indicate the dip direction by tick marks on the downthrown side of the fault. Dip direction can be determined from field observations and from the aerial photographic expression of a fault. The dip angle (measured in a vertical plane) requires subsurface data, and that is available for only two of the 7 faults. However, a dip angle for the others can be estimated by considering the range of dip angles reported for hundreds of other surface faults throughout the Houston area. At shallow depths, those dips normally range from 300 to 400 percent slope (71 to 76 degrees from the horizontal). Horizontal ground movement perpendicular to the compass direction of the fault is extensional and approximately 25 to 33 percent of the vertical component.

III. SURFACE EXPRESSION OF FAULTS THAT CROSS MONROE ROAD.

Examination of works of man in the Hobby Airport area show that fault movement here has proceeded at very low rates over the past 30 to 35 years. Reports written in the 1970s often describe ground elevation changes of a few to several inches across fault zones, as measured in buildings and on paved surfaces. Attendant with widespread commercial development in recent years, these elevation changes have been significantly altered or obliterated. As a consequence, it is now very difficult to find convincing field evidence of fault disturbance zones there. This is especially true along a segment of Monroe Road between Airport Boulevard and Almeda Genoa Road. Construction of it began in the early 1980s. Aerial LiDAR images have not proven useful for fault investigations in this area as they fail to reveal fault scarps less than about 6 inches high.

None of the active faults now known in the Hobby Airport area show topographic relief on a 1-foot contour interval topographic map prepared by the U.S. Geological Survey in 1915 (Park Place quadrangle). Absence of topographic expression implies that the faults were inactive, or only slightly active in the decade or two prior to 1915. Several faults in other parts of Harris County do show topographic expression on other quadrangles in this series of maps.

During repeated visits to each of the 7 faults over the past 4 months, I find little to no surface expression of them where they cross fields and man-made structures in the near vicinity of Monroe Road. Field mapping, the exploration method that yields the highest level of accuracy for locating faults, is largely ineffective at this location and this time. As a consequence, mapping their traces across Monroe Road derives primarily from studies of aerial photographs, from reference to a report published in 1978 (Verbeek, E. R., and Clanton, U. S., 1978, Map showing surface faults in southeastern Houston metropolitan area, Texas, U.S.G.S. Open-File Report 78-797, 20 pp.) and from 19 proprietary reports written mostly in the 1980s and 1990s. Plate II is a copy of a portion of Verbeek and Clanton's map that covers the Hobby Airport area. Note that Monroe Road on that map is "Old Monroe", which is now part of Hobby Airport. "New" Monroe Road is approximately 700 feet east of it. The report does not discuss individual faults in detail.

IV. DESCRIPTION OF THE FAULT CROSSINGS

Below are separate descriptions of the 7 surface faults, applicable to the area where they cross Monroe Road between Airport Boulevard and Almeda Genoa Road. Each fault is designated by the number Verbeek and Clanton assigned it in 1978 (Plate II).

A. Fault No. 10

The surface trace of Fault No. 10 appears only a few tens of feet east of the north-bound lanes of Monroe Road at Airport Boulevard. It crosses Monroe's centerline about 400 to 600 feet south of the centerline of Airport Boulevard. Here the fault trends N33E and dips to the southeast. South of Airport Boulevard, at the west side of the Shell service station, an 85-foot long open crack in concrete pavement parallels the fault trace. The crack is about 30 feet east of the north-bound lanes of Monroe Road. There are other similar pavement cracks in this vicinity, but none as pronounced. I did not find an unusually high frequency of pavement cracks or an unusual warping of pavement where the fault crosses the north- and south-bound lanes of Monroe.

Geophysical logs of five 300-foot deep exploratory boreholes confirmed the existence of Fault 10 on a tract just north of the intersection of old Monroe Road and Airport Boulevard. The 1983 study reported an estimated movement rate of 0.2 inches per year. I found no reference to a measured width of the zone of disturbed ground at any point along Fault 10, but studies of other faults in the area report widths in the range of 20 to 30 feet.

A waterline down the central axis of Monroe will pass within the fault zone for a distance of approximately 200 feet. Strain rates will be highest at the north edge of the zone. Nevertheless they can be expected to be unusually low because the Monroe crossing area is very near the southwest end of this 0.54-mile long fault.

B. FAULT NO. 21

Fault 21 extends 1.9 miles in direction N30E, crossing the centerline of Monroe Road approximately 70 feet north of the centerline of Panair Street. Ground southeast of the fault trace moves downward and southeastward relative to ground on its northwest side. The fault trace crosses the centerline of Panair Street 50 to 55 feet west of the centerline of Monroe. Thus the local trend of the fault is N37E. I reported these data after completing studies of the fault in November 1982 and June 1999. Judging from 1982 observations of man-made structures disturbed by the fault, its zone of intense deformation in the Monroe-Panair area is approximately 20 feet wide. Due to uncertainties in determining a precise location for the fault trace, it was deemed prudent to establish a 50-foot wide fault zone. The reports noted that "new" Monroe had been constructed during the summer of 1982, and that its location had been obscured in the "new" Monroe-Panair area. The result was that mapping of the fault relied on previous field observations and a study of aerial photographs.

At the present time there is no conclusive field evidence of the fault along its trend in the Monroe-Panair area, which suggests it has been essentially inactive there since 1982. I found no evidence of an elevation change or a vegetation anomaly in an open field between Panair and Airport Boulevard. However, gently warped and cracked pavement appears on the southeast-bound lanes of Airport Boulevard approximately 670 feet southeast of the centerline of Monroe. It occurs at the southeast end of a bridge over a north-south drainage channel. The bridge and road surface were constructed in 1978 when Panair was widened from 2 to 4 lanes.

In 1982 the fault passed beneath a building, since removed, approximately 1000 feet southwest of the Monroe-Panair intersection. A previous owner provided data on the rate of movement of Fault 21. An overhead rail in the building dropped 2 inches west to east between 1971 and 1981, yielding an average movement rate of 0.2 inches per year.

C. FAULT NO. 16A

Verbeek and Clanton's 1978 map shows a single Fault No. 16, but lineaments appearing on a 1974 aerial photograph, strongly suggest 2 overlapping en echelon fault segments. Both segments trend toward the northeast and are downthrown to the southeast. The 1978 map marks the central portion of the fault with a dashed line, indicating the authors' uncertainty as to the fault's location there. The dashed portion is where the offset occurs.

Based on aerial photographic evidence, the northernmost segment, Fault 16A, is about 1100 feet long. It crosses the centerline of Monroe Road in direction N30E approximately 640 feet south of the centerline of Panair Street. I found no clear evidence of the fault on either the north- or south-bound lanes of Monroe.

Near its northeast end Fault 16A crosses Panair at a point about 435 feet east of the centerline of Monroe. Here it has gently warped and cracked the paved surface of Panair. In December 1980 I measured 7 inches of vertical offset of an older paved surface on Panair at this same location. Not knowing the date the surface had been constructed, I was unable to obtain a rate of movement for the fault. Because the fault is so short and has minimal surface expression, its movement rate over the past 3 decades must have been extremely low.

D. FAULT NO. 16B

Aerial photographic lineaments associated with the trace of Fault No.16B trend in direction N39E. Ground is downthrown on the southeast side of the fault. Where the fault crosses the centerline of Monroe, approximately 920 feet south of the centerline of Panair Street, there is presently no clear field evidence of its existence. However, about 100 feet southwest of that point the fault may be revealing its presence in the form warped sidewalk at the west edge of Monroe, as well as a substantial foundation crack 30 feet south of the northeast corner of a commercial building occupied by Pantex-Emmerfield Systems.

A 1981 study of a tract extending between Monroe and Old Monroe just north of Bryant Street encountered the fault in 3 parallel trenches spaced 110 and 150 feet apart. Between the ground surface and the 8-foot depth of the trenches, the fault dipped 75 to 80 degrees to the southeast. The zone of disturbed ground along the fault was estimated to be 10 feet wide. No data were available to determine a rate of movement for the fault.

E. FAULT NO. 17

Verbeek and Clanton's 1978 map shows Fault No. 17 approaching Monroe Road from the northeast, but not crossing it. The northwest side of the fault is downthrown. I found no field or aerial photographic evidence of it where it would project across Monroe Road. Evidence from a

U.S. Department of Agriculture aerial photograph (BQY 4T-70, 3-26-1957) indicates that Verbeek and Clanton's Fault No. 17 is continuous with the northern part of Fault No. 15. At the southwest end of this northern segment is a southeastward 250-foot overlapping en echelon offset toward the north end of the southern segment of Fault No. 15. From there No. 15 crosses Monroe and continues southwestward to, and perhaps across, Old Monroe.

F. FAULT NO. 15

The trace of Fault No.15's southern segment crosses the centerline of Monroe in direction N32E approximately 875 feet north of the centerline of Scranton Street. The paved surfaces of both the north- and south-bound lanes of Monroe are uneven, but not significantly warped where the fault lineament crosses them. At the west edge of Monroe's southbound lanes is a steel pole at the south edge of a driveway to the Wire Coil Manufacturing Company. An employee of the plant stated that after a heavy rainfall, water stands on Monroe northwest of a line passing from the pole northeastward across Monroe. Those conditions correspond well with the direction and movement sense of Fault No. 15. Along the east side of Monroe I found no field evidence of fault-related disturbance to buildings, parking areas or a circular pool, all of which lie along the aerial photographic lineament associated with this fault. Those structures appear on a 1998 photo, but not on one taken in 1990. The fault is likely there, but is currently inactive.

G. FAULT NO. 20

The trace of Fault No. 20 crosses the centerline of Monroe approximately 160 feet north of the centerline of Scranton Street. In turn, it crosses Scranton about 100 feet west of the centerline of Monroe. The local trend of the fault here is N32E. Ground northwest of the fault trace moves downward and northwestward relative to ground southeast of it.

An intensive search for field evidence of the fault in the vicinity of the street intersection failed to reveal any convincing evidence of its presence. I found no evidence of a fault scarp in the wooded area northeast of the Monroe-Scranton intersection. Properties southwest of the intersection have been developed too recently to show evidence of a minimally active fault. Accordingly, data on the fault's location and directional trend are established entirely from its expression on aerial photographs. To the best of my knowledge, no shallow subsurface investigations or elevation surveys have been conducted to gain information on the location, trend or movement rate of this fault.

H. FAULT NO. 25

Fault No. 25 is the southernmost fault that crosses Monroe Road between Airport Boulevard and Almeda Genoa Road. It trends in direction N34E and dips to the northwest. Its aerial photographic lineament extends for approximately 1.9 miles from a point near the intersection of Gulf Meadows Drive and Fuqua Street to a point about 0.25 miles northeast of the intersection of Monroe Road and Meldrum Lane.

Several streets in residential subdivisions southwest of the Monroe-Meldrum intersection show low topographic scarps across the fault, but presently there is no field evidence of the fault on either Monroe or Meldrum. Neither is there evidence of fault-related disturbance to the concrete liner in a drainage channel along the north side of Meldrum. Its wetted perimeter gives no indication of either lateral or vertical displacement that could be attributed to disruption by an active fault. On the other hand, aerial photographic lineaments associated with Fault No. 25 indicate that it crosses Monroe right at its intersection with Meldrum. The lineaments appear on photographs taken in 1957, 1972, 1974, 1976, 1977, 1978 and 1980. New construction in the area obliterated the lineament in the Monroe-Meldrum area on aerial images taken in 1982 and later. These observations attest to the existence of Fault No. 25, and they suggest it has been essentially inactive since at least 1982 in the area where it crosses Monroe.

V. RATE OF DIFFERENTIAL MOVEMENT OF THE FAULT BLOCKS

The preceding descriptions provided actual movement data for only one fault, Fault No. 21. Rates for the other faults are estimated from data on nearby faults that are not part of this study. The estimates ranged from "inactive" to 0.2 inches per year over a ten-year period. At the present time, not enough is known about the mechanism and dynamics of the faulting process in the Houston area to make reliable predictions of future movement rates. Nor is it possible to predict which of the 7 faults, if any, will be active during any time interval in the future. It is the nature of faults to undergo episodic movements, and the present "quiet" time should be regarded as temporary. For design purposes it may be best to assume a vertical movement rate of 0.2 inches per year for each fault that crosses Monroe Road. The horizontal extensional component for each fault is estimated to be 0.1 inches per year in direction S 60 E.

VI. RECOMMENDATIONS FOR ADDRESSING THE FAULT PROBLEM

Fault zones in the Hobby Airport area are approximately 20 feet wide, but because the 6 of the zones trend only 30 to 35 degrees from the direction of the planned waterline route, flexibility for the waterline should be provided through approximately 280 feet of disturbed ground. Adding in Fault No. 10, which crosses Monroe at a much smaller angle, the total length of the zone to be protected rises to about 500 feet. When uncertainty as to the exact location of the faults is also taken into account, the total length of the protection zone increases to about 1000 feet.

Normally Phase I fault investigations deal with only a single fault that impacts a project area. This project offers a much more complicated scenario where a waterline must cross 7 closely spaced, active faults. Most of the extensional strain of ground between Airport Boulevard and Almeda GenoaRoad is localized at the fault zones, but it should be anticipated that some may accumulate in areas between those zones. Rather than thinking about dealing with each fault separately, a mitigation plan that would address all the faults, as well as the ground between them, may be a better approach.

Oil and gas pipeline companies have operations in the dry southwestern states where large desiccation cracks form to depths of 10 feet or more. Here engineers must design shallow-buried pipelines that will accommodate large amounts of extensional ground strain. Their solution to the problem is to lay the pipeline in an open trench wide enough to allow the pipe to meander from one side of the trench to the other. As horizontal ground strain accumulates, the pipeline straightens somewhat without rupturing. The meander simultaneously provides flexibility that will accommodate vertical strains.

If plans call for deep burial in poorly consolidated soils, a meandering waterline could be placed in a sufficiently wide slurry trench. Whether a meandering line could be placed in deep trenches where a vertical shaft-horizontal bored tunnel construction method is used would have to be addressed by pipeline engineers.

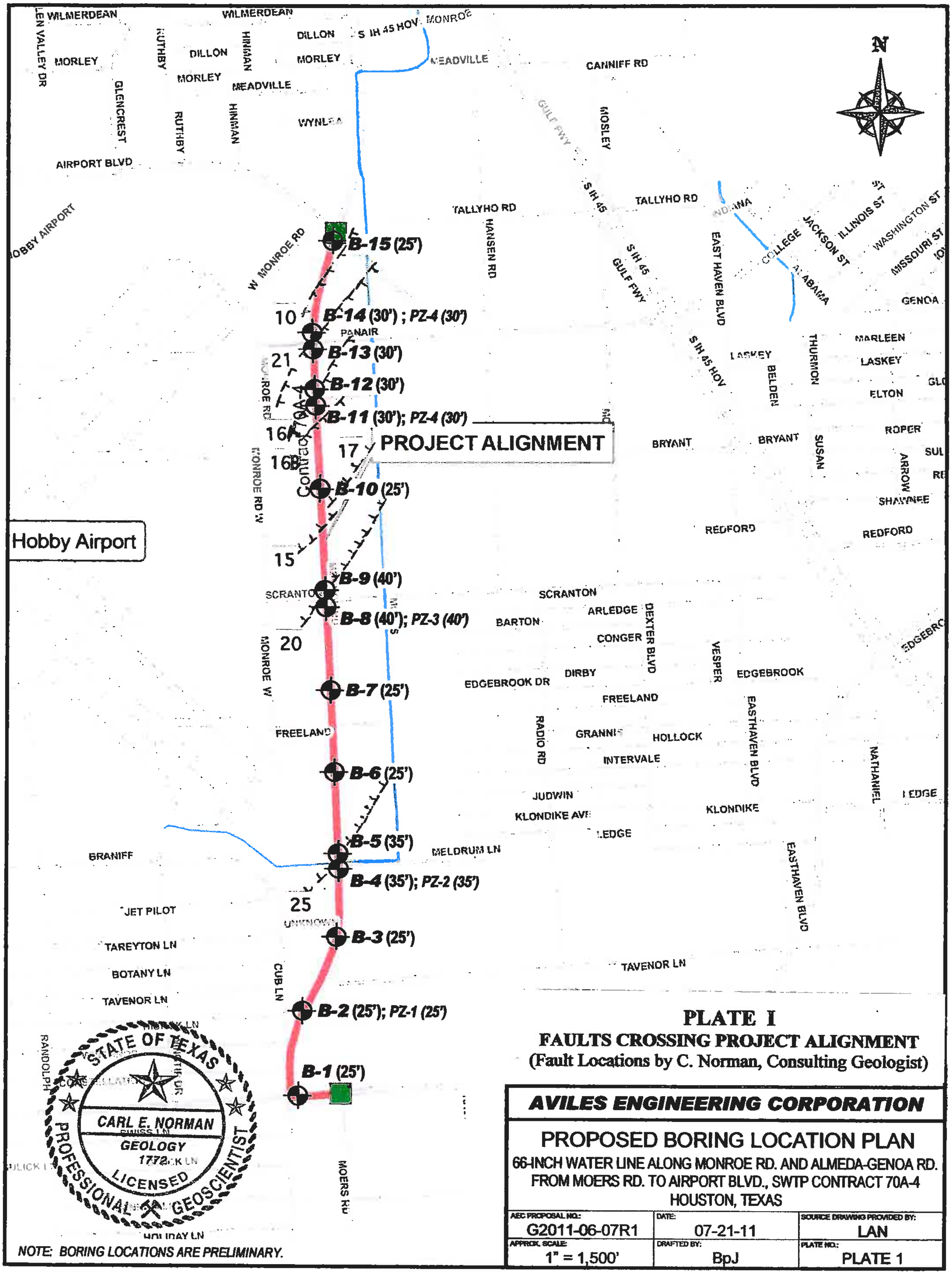

PLATE I

FAULTS CROSSING PROJECT ALIGNMENT

(Fault Locations by C. Norman, Consulting Geologist)

AVILES ENGINEERING CORPORATION

PROPOSED BORING LOCATION PLAN

66-INCH WATER LINE ALONG MONROE RD. AND ALMEDA-GENOA RD.
FROM MOERS RD. TO AIRPORT BLVD., SWTP CONTRACT 70A-4
HOUSTON, TEXAS

AEC PROPOSAL NO.:	DATE:	SOURCE DRAWING PROVIDED BY:
G2011-06-07R1	07-21-11	LAN
APPROX. SCALE:	DRAFTED BY:	PLATE NO.:
1" = 1,500'	BpJ	PLATE 1

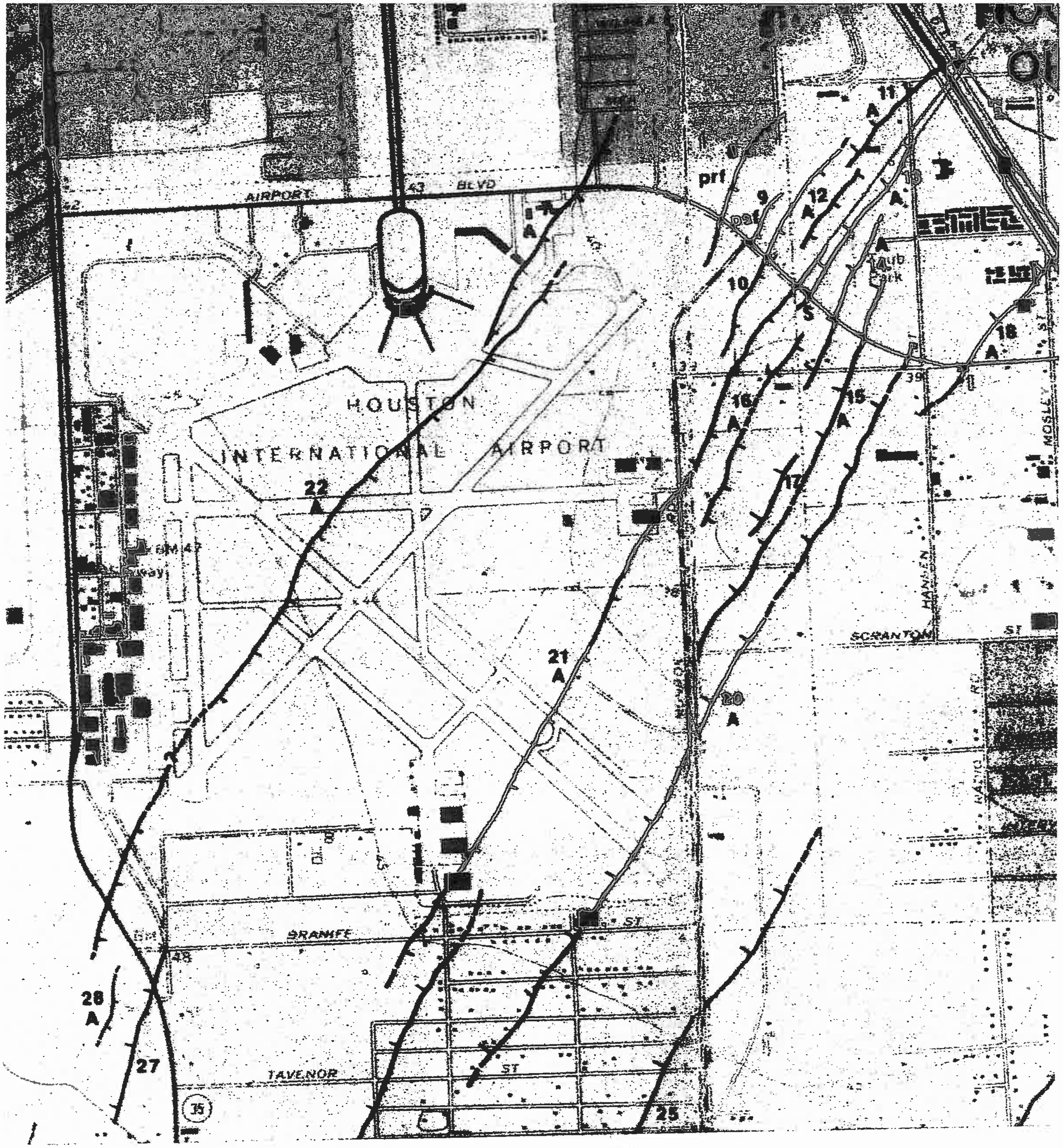

PLATE II

MAP SHOWING SURFACE FAULTS IN SOUTHEASTERN
HOUSTON METROPOLITAN AREA, TEXAS
(From Verbeek & Clanton, 1978, U. S. G. S. Open File Report 78-797)